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Evidence of Orbital Motion in the Binary Brown Dwarf Kelu-1AB

Christopher R. Gelino and S. R. Kulkarni

California Institute of Technology, Geological and Planetary Sciences, MC 150-21, 1200 East California Boulevard, Pasadena, CA 91125; cgelino@gps.caltech.edu, srk@astro.caltech.edu

and

Denise C. Stephens

Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218; stephens@pha.jhu.edu

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ABSTRACT. We have resolved Kelu-1 into a binary system with a separation of ∼290 mas using the Laser Guide Star Adaptive Optics system on the Keck II telescope. We have also reanalyzed a 1998 *HST* observation of Kelu-1 and find that the observed PSF is best fit by a binary object separated by 45 mas. Observations at multiple epochs confirm that the two objects share a common proper motion and clearly demonstrate the first evidence of orbital motion. Kelu-1B is fainter than Kelu-1A by 0.39 ± 0.01 mag in the K' filter and 0.50 ± 0.01 mag in the H filter. We derive spectral types of L2 ± 1 and L3.5 ± 1 for Kelu-1A and B, respectively. The separation of flux into the two components rectifies Kelu-1's overluminosity problem, which has been known for quite some time. Given the available data, we are able to constrain the inclination of the system to $>81°$ and the orbital period to $\gtrsim 40$ yr.

1. INTRODUCTION

L dwarfs are a class of objects with spectral types cooler than the latest M dwarfs (Kirkpatrick et al. 1999). Their population consists of both substellar (i.e., brown dwarfs) and stellar mass objects, with the brown dwarfs being identified by the presence of Li I absorption at 6708 Å in their spectra. Kelu-1 was one of the first such brown dwarfs discovered. It was found at a trigonometric distance of 18.7 pc (Dahn et al. 2002) as part of a proper-motion survey (Ruiz et al. 1997). Since Kelu-1's discovery, more than 400 L dwarfs have been classified[1] in large surveys such as the Deep Near-Infrared Survey (DENIS), the Two Micron All Sky Survey (2MASS), and the Sloan Digital Sky Survey (SDSS). A spectral class sequence was established (Kirkpatrick et al. 1999, 2000; Martín et al. 1999b), and Kelu-1 was subsequently assigned a spectral type of L2 in the optical (Kirkpatrick et al. 1999) and L3 in the near-IR (Knapp et al. 2004). These other discoveries provided a baseline against which to compare Kelu-1's other characteristics. For example, it was quickly realized that Kelu-1 was much brighter than other L2 dwarfs, causing Martín et al. (1999b) to first suggest that Kelu-1 might be a binary. This superluminosity has been seen in other studies (Leggett et al. 2001; Golimowski et al. 2004) where the main source of this overbrightness was attributed to either an unresolved binary or a young age.

Martín et al. (1999a) observed Kelu-1 on 1998 August 14 with the NICMOS camera on the *Hubble Space Telescope* (*HST*), and no companions were found for separations greater than 300 mas and magnitude differences <6.7 mag (F165M filter). Koerner et al. (1999) observed Kelu-1 in a non-AO, seeing-limited program on Keck I using the NIRC instrument on 1998 February 14 and 1999 February 9. Because Kelu-1 had a fairly circular point-spread function (PSF) during these observations (PSF FWHM ≈ 0″.27), it was used as a PSF star for the other companion search targets of their project. While these observations did not discount Kelu-1 as being a very close, unresolved binary, they did warrant a look at the young-age hypothesis.

On the basis of the strength of the Li I absorption feature, Basri et al. (1998) constrained the age of Kelu-I to be 0.3–1 Gyr. With this age range and Kelu-1's brightness, it should have an effective temperature of 2100–2350 K, about 400 K higher than objects with similar spectral types (Golimowski et al. 2004). For it to have an effective temperature consistent with other L3 dwarfs, Golimowski et al. suggest that Kelu-1 must have an age of ∼10 Myr, more than an order of magnitude lower than the Li I-established lower age limit. These discrepancies mean that a young age is unlikely to be the cause of the overluminosity.

Aside from the luminosity, there is other evidence that supports the binarity of Kelu-1. It is reported to be photometrically and spectroscopically variable with a period of 1.8 hr (Clarke et al. 2002, 2003). If this period corresponds to an orbital period, then the system would likely be circularized, and the

[1] See http://dwarfarchives.org for a complete list of all known spectroscopically determined L dwarfs.

TABLE 1
NIRC2 Plate Scales and Rotation Angles

Date (UT)	Scale (mas pixel^{-1})	Rotation (deg)	Dither Positions
2005 Mar 4	9.97 ± 0.02	$+0.08 \pm 0.04$	5
2005 Apr 30	9.96 ± 0.02	$+0.11 \pm 0.03$	4

orbital radius of the system would be less than a solar radius (Clarke et al. 2002). In addition, Clarke et al. (2002) claim that the ∼120 km s^{-1} radial velocity produced by a very close binary such as this could account for the large line broadening (60 ± 5 km s^{-1}) measured by Basri et al. (2000).

We are conducting an adaptive optics (AO) survey of L and T dwarfs at the Keck Observatory in an effort to determine binarity in these objects (an article describing the full details of this project is in preparation). Because of the intrinsic faintness of L and T dwarfs (magnitudes for Kelu-1 are $V = 22.1$ and $R = 19.2$; Ruiz et al. 1997), it is not possible to use them as natural guide stars (NGS), for which the magnitude limit is about $V = 14$. Instead, we use the newly commissioned Laser Guide Star Adaptive Optics system (LGS AO),[2] in which the wave front corrections are performed on a layer of sodium atoms 80 km high in the Earth's mesosphere, which are excited by a 10–14 W laser tuned to 598 nm. The projected laser and returned light propagate along the same path, requiring the use of a natural star (or other pointlike astronomical source) for tip-tilt measurements. The tip-tilt reference can be as faint as $R = 18.5$, but must be within 60″ of the science target. Thus, the area of sky reachable with AO is greatly increased by the less stringent requirements for a reference star provided by the used of the LGS, and many L and T dwarfs binaries can be observed with high-resolution imaging from the ground. We included Kelu-1 in our survey in an effort to resolve the controversy over its binarity and overluminosity and to search for any low-mass companions. In this article we discuss the detection of a companion to Kelu-1, first reported in Liu & Leggett (2005), and show the first evidence of orbital motion of the companion.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Keck LGS AO

Observations of Kelu-1 were obtained with NIRC2 (K. Matthews et al., in preparation) behind the LGS AO system on 2005 March 4 and April 30 during shared-risk time. A suitable tip-tilt reference star (ID 0643-0289866, $R = 14.3$, separation 27″) was identified in the USNO-B 1.0 catalog (Monet et al. 2003). Skies were photometric on both nights, and the AO system provided very good corrections on our targets. Kelu-1 was observed with the K' filter during both epochs, with additional exposures in the H filter during follow-up observations in April. These filters were chosen to maximize the Strehl ratio in our images. The data were reduced using custom and public IDL scripts.

For each night, two sets of reduced images were produced from the data, a photometric set and an astrometric set. The only difference in these sets is that an image distortion correction was performed on the astrometric data set. The distortion in the narrow camera is negligible within a region a few hundred pixels on a side around the center of the chip, and gradually increases to as much as 4–5 pixels near the edge. While the correction fixes the distortion with residuals of 0.81 and 0.62 pixels in the x and y directions, respectively, it does not preserve flux information. Consequently, it is not suitable for use in images intended for photometric analysis.

The plate scale for both nights was determined using astrometric images of the core of the globular cluster M5. This field was observed with WFPC2 on *HST*, with the stars in common with our observations present in the Planetary Camera. We imaged this field with a four (in April) or five (in March) position dither pattern in the narrow camera (≈10″ field of view). From the WCS information in the *HST* image headers, we determined the sky positions of several stars present in our NIRC2 images. These positions were then used to calculate the plate scale and rotation angle for each position in the dither. The average of these values is the resulting scale and rotation for that night. The errors in these quantities are equal to the standard deviation of the measurements. Table 1 presents the plate scale for these nights.

In our March 4 images of the Kelu-1 field, we saw what appeared to be a binary object with a separation ∼300 mas and a differential K' magnitude of ∼0.4. In order to obtain proper motion confirmation of the companion, we reobserved this system on April 30. At both epochs, we determined the separation and position angle of the candidate companion by using an average of measurements on the individual reduced astrometric images. The errors are the standard deviations of these measurements. Table 2 shows these results. The moderately large proper motion of Kelu-1 is 285.0 ± 1.0 mas yr^{-1} at $272.^\circ2 \pm 0.^\circ2$; Dahn et al. (2002) made it possible to confidently confirm physical companionship based on observations separated by only 2 months. The measured positions of the companion were about 15 σ away from its predicted background position, clearly demonstrating that these two objects have a common proper motion and are physically associated. Our binary conclusion firmly supports the recent announcement of Kelu-1's binarity from Keck LGS AO observations obtained in 2005 May (Liu & Leggett 2005).

For both nights, all of the photometric images were offset such that northeast object was in the same location in the overlap region. This image stack was then median-averaged to obtain the final image (Fig. 1), on which the photometry was performed. The components were well separated, and no PSF subtraction routines were needed. No photometric standards were observed on either night, so only differential photometry is shown in Table 3. The northeast object is the brighter com-

[2] See http://www2.keck.hawaii.edu/optics/lgsao.

TABLE 2
KELU-1B ASTROMETRY

Date (UT)	Separation (mas)	P.A. (deg)	Reference
1998 Aug 14	45 ± 18	[38.0 or 218.0] ± 11.9[a]	This work
2005 Mar 4	284.3 ± 0.8	220.9 ± 0.3	This work
2005 Apr 30	289.3 ± 0.7	221.1 ± 0.1	This work
2005 May 1	291 ± 2	221.2 ± 0.6	Liu & Leggett (2005)
2005 Jul 31	298 ± 3	221.3 ± 0.9	This work[b]

[a] Because the objects are unresolved, there is a 180° ambiguity in the position angle solution.
[b] Based on *HST* observations by W. Brandner that are present in the public archive.

ponent in both the H and K'. It will henceforth be called Kelu-1A, and the fainter southwest component Kelu-1B. Our measured astrometry and differential photometry are consistent with those of Liu & Leggett (2005).

2.2. *HST* NICMOS

We reexamined E. Martín's 1998 *HST* NICMOS images using the PSF modeling technique described in Stephens & Noll (2006). In short, this technique involves the subpixel shifting of two model PSFs and iteratively changing the relative brightness of the PSFs to obtain the minimum residual for each shifted pair. The lowest minimum residual for all shifted pairs represents the best fit for the observed PSF. Our analysis discovered that the observed PSFs in all three filters (F110M, F145M, and F165M) were better fit by double-PSF solutions than they were by single-PSF solutions. The derived astrometry of the components is presented in Table 2. Because the objects are unresolved, a 180° ambiguity exists in the value of the position angle.

It is also possible to estimate the magnitudes of the two components (listed in Table 4) using this technique. Because the two components are unresolved, the determination of the individual magnitudes is subject to systematic uncertainties in the fitting process; it is difficult to quantify this uncertainty. Consequently, although these calculations may not determine the actual difference in magnitudes between the two components, they do indicate the reliability of a binary solution. Furthermore, the computed magnitudes are also correlated, so if one object is actually fainter than computed, the other component would be brighter, thus conserving the total flux in the system.

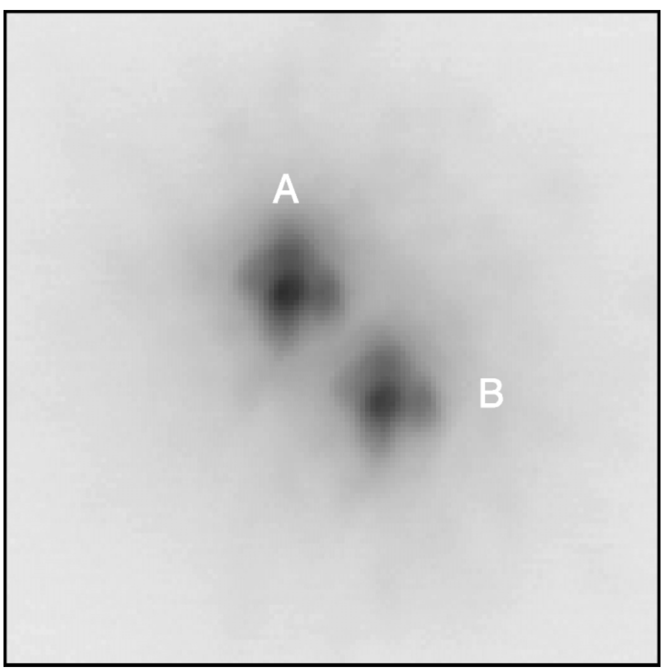

FIG. 1.—K' image of Kelu-1AB taken on 2005 March 4. The image is 1.″2 on a side; north is up and east is to the left. Kelu-1B is located 284.3 ± 0.8 mas at a position angle of 220.°9 ± 0.°3 from Kelu-1A.

3. DISCUSSION

3.1. Component Characteristics

The spectral types of the components can be estimated using the photometry and absolute magnitude–spectral type relation in Vrba et al. (2004) and the differential photometry presented here. For this exercise we assume that the ΔH and $\Delta K'$ measurements in this study are equivalent to ΔH and ΔK in the CIT photometric system as employed by Vrba et al. While we know that this is not the case, our interest is only in *approximately* determining the spectral types of the components; the *only* way to determine spectral types for these or any other objects is to obtain properly calibrated spectra. Based on the multisystem, near-IR photometry study of Stephens & Leggett (2004), we conservatively impose an additional photometric error of 0.15 mag for using this assumption. This error is added in quadrature to our measured photometric errors.

TABLE 3
KELU-1AB PHOTOMETRY

Date (UT)	Filter	Δmag
2005 Mar 4	K'	0.39 ± 0.01
2005 Apr 30	K'	0.39 ± 0.01
	H	0.50 ± 0.01

TABLE 4
Kelu-1AB Derived Properties

Property	A	B
Spectral Type	L2 ± 1	L3.5 ± 1
H magnitude	12.99 ± 0.15	13.49 ± 0.15
K magnitude	12.37 ± 0.16	12.76 ± 0.16
F110M magnitude	14.30 ± 0.04	15.13 ± 0.10
F145M magnitude	13.83 ± 0.10	14.04 ± 0.13
F165M magnitude	13.03 ± 0.07	13.35 ± 0.11
Mass ($M_\odot$)	0.060 ± 0.01	0.055 ± 0.01
$T_{\rm eff}$ (K)	1900–2100	1700–1900

The $H_{\rm CIT}$ and $K_{\rm CIT}$ apparent magnitudes of Kelu-1AB are 12.46 ± 0.04 and 11.80 ± 0.03, respectively (Dahn et al. 2002). Coupled with our measured $\Delta H = 0.50 \pm 0.15$ and $\Delta K' = 0.39 \pm 0.15$, the apparent magnitudes of the resolved components become $H_{\rm A} = 12.99$, $K_{\rm A} = 12.37$, $H_{\rm B} = 13.49$, and $K_{\rm B} = 12.76$ (Table 4). Converting these magnitudes from apparent to absolute and applying equations (2) and (3) from Vrba et al. (2004) yields a spectral type of ∼L2 ± 1 for Kelu-1A and ∼L3.5 ± 1 for Kelu-1B. These estimates are consistent with the optical and near-IR spectral types of the composite system and with the spectral types derived by Liu & Leggett (2005).

With this photometry and these spectral type estimates, we can place these objects on magnitude-spectral type diagram. Figure 2 presents a modified version of Figure 4 of Vrba et al. (2004). In agreement with Liu & Leggett (2005), it is quite clear that the overluminosity of Kelu-1AB is caused by the unresolved binary and not by an unusually young effective temperature-based age (Golimowski et al. 2004).

Finally, we can estimate the effective temperature from the photometry presented here. Golimowski et al. (2004) calculate a K-band bolometric correction (BC_K) for Kelu-1AB of 3.31 ± 0.07. While this calculation is independent of the spectral type of Kelu-1AB, the spectral type used for Kelu-1AB and all of the other objects in that study were based on near-IR spectra. The spectral types for Kelu-1A and B presented here are based on a relation derived from optical spectral types. The near-IR spectral type of Kelu-1AB is L3 ± 1 (Knapp et al. 2004), whereas the optical spectral type is L2 ± 0.5 (Kirkpatrick et al. 1999). As discussed in Kirkpatrick (2005), it is neither uncommon nor unexpected for L and T dwarfs to be classified differently in the optical and near-IR. Consequently, it is unclear what value of BC_K should be used from Golimowski et al. (2004).

Fortunately, for early L dwarfs such as Kelu-1A and B, the range of BC_K is quite small. The average value of BC_K for objects with near-IR spectral types L0–L5, inclusive, is 3.32, with a standard deviation of 0.07. Since this average value is consistent with the value of BC_K computed for the unresolved Kelu-1AB, we choose the unresolved value as the bolometric correction for the individual components. We note, however, that the uncertainty in the effective temperature determination is largely dominated by the unknown age of Kelu-1, and given the constraints on the bolometric corrections of early L dwarfs, the exact value of BC_K is unimportant.

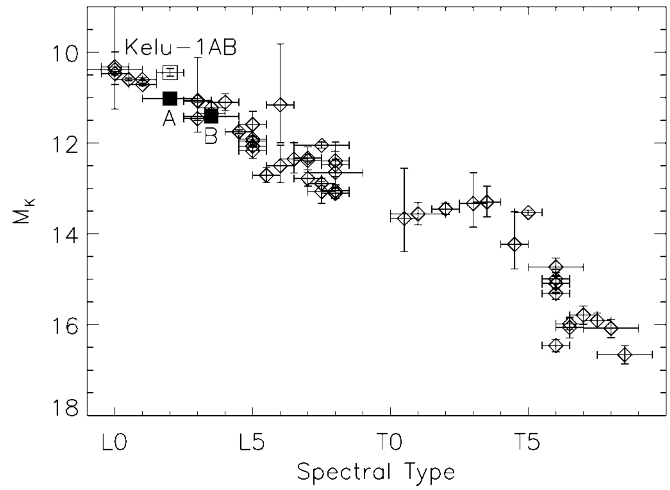

Fig. 2—Absolute K magnitude as a function of spectral type for the objects in Table 7 of Vrba et al. (2004). The position of the unresolved Kelu-1AB is marked as an open square; the individual components are shown with filled squares. The binarity rectifies the well-documented overluminosity in the K band.

On the basis of our photometry, the absolute K magnitudes of Kelu-1A and B are 11.02 and 11.41, respectively. Assuming a K-band bolometric correction of 3.31 for each component yields bolometric magnitudes of 14.33 and 14.72 and luminosities $\log(L/L_\odot)$ of −3.83 and −3.99. Finally, using an age range of 0.3–1 Gyr (Basri et al. 1998) and the Chabrier et al. (2000) DUSTY atmosphere models, we determine an effective temperature range for Kelu-1A of 1900–2100 K and for Kelu-1B of 1700–1900 K (Table 4). Liu & Leggett (2005) computed effective temperatures for Kelu-1A and B (2020 and 1840 K) by scaling the effective temperature of Kelu-1AB (Golimowski et al. 2004) by their luminosity calculations. Despite the differences between our method and theirs, our results are completely consistent.

3.2. System Characteristics

It is not known whether the Li I absorption at 6708 Å detected by Ruiz et al. (1997) and others is from one or both components. Liu & Leggett (2005) suggest that the presence of any lithium in the unresolved spectrum indicates that both components are substellar and, at the very least, that Kelu-1B bears lithium in its atmosphere. Consequently, the masses of both components must be $\lesssim 0.065\ M_\odot$ (Chabrier & Baraffe 1997; Basri 1998). To estimate component masses, we use the photometry derived here along with the age estimate of Basri et al. (1998) to place the system components on the DUSTY atmosphere model evolutionary tracks (Chabrier et al. 2000). From the combined mass estimates presented in Figure 3, we estimate the mass of Kelu-

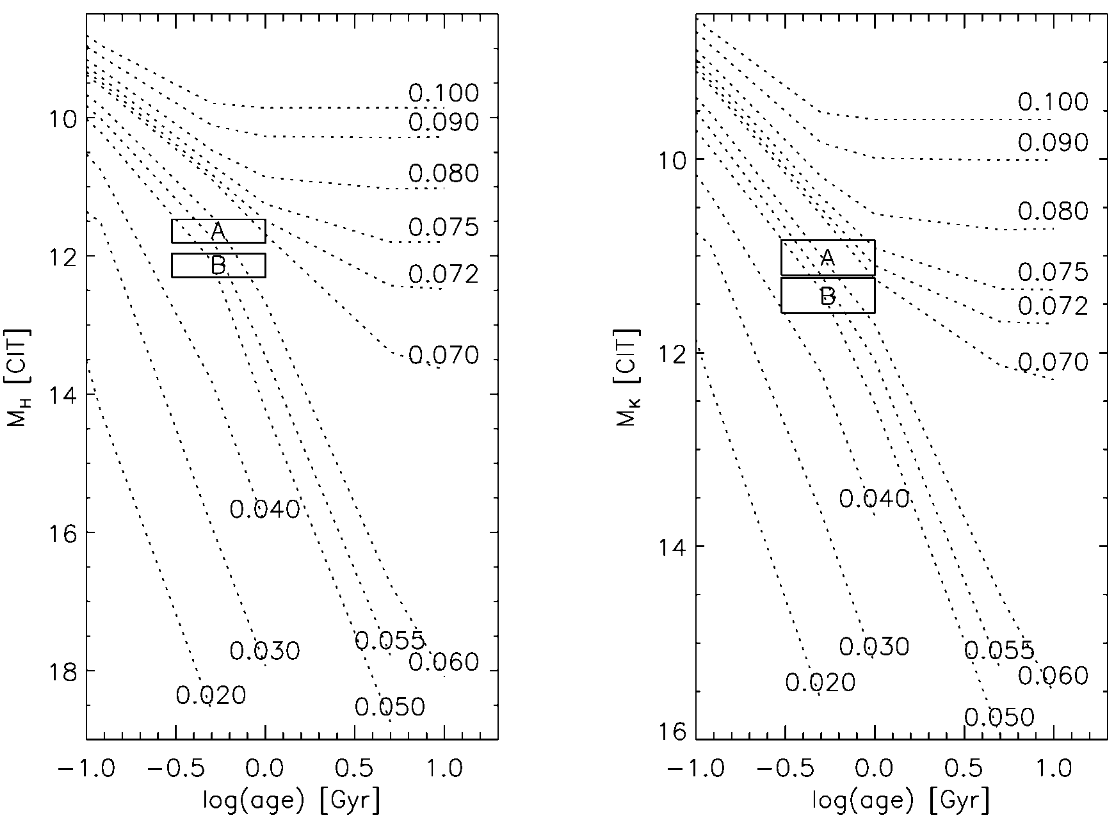

FIG. 3—*Left*: Absolute *H* magnitude as a function of age for Kelu-1A, Kelu-1B (*boxed regions*), and the DUSTY models (*dotted lines*) for masses from 0.1 to 0.02 $M_\odot$ (*top to bottom*). *Right*: Same as at left, but for absolute *K* magnitude. The age range is derived from the strength of the Li I absorption feature in the composite spectrum Basri et al. (1998). The combined estimate for the masses of Kelu-1A and B are 0.060 ± 0.01 $M_\odot$ and 0.055 ± 0.01 $M_\odot$, respectively.

1A to be 0.060 ± 0.01 $M_\odot$ and that of Kelu-1B to be 0.055 ± 0.01 $M_\odot$, in good agreement with the mass estimates derived by Liu & Leggett (2005). Even though the conservative errors on these masses do include stellar masses, as mentioned above, the true masses are not likely to be greater than about 0.065 $M_\odot$. Of course, by following the orbital motion of the companion over time, it will be possible to derive dynamical masses, which will provide much needed constraints on the models.

The computation of these dynamical masses will be some time in coming. Table 2 presents all of the known astrometry of the Kelu-1AB system as of 2006 January. It is quite clear from this astrometry that Kelu-1B has exhibited orbital motion from the time it was first resolved (our 2005 March 4 observation) to the time of its last observation (a public archival *HST* observation on 2005 July 31, obtained by W. Brandner). In fact, the displayed motion suggests that the companion is still moving toward apoapsis. During this nearly 5 month period, the rate of change in the separation has not changed significantly, and there is insufficient phase coverage to determine a reliable orbit. Nonetheless, we can make some crude estimations of the orbit based on the available data.

Given so few points in the orbit, it is impossible to determine how much of the nearly linear motion is caused by a high inclination, very high eccentricity, or both. In order to simplify the discussion, we assume that the orbit is circular, and thus is being viewed nearly edge-on.

The most recently measured 2005 positions and the 1998 PSF-modeled position provide some tight constraints on the inclination of the orbit. Although the position angle of the four resolved measurements is not significantly changing, it is not possible to extend a line connecting all four of these points directly back to Kelu-1A. Therefore, the inclination of the orbit must be <90°. We can get a rough estimate of the minimum inclination by assuming that the maximum extent perpendicular to the 2005 July position is the separation of the modeled PSFs in 1998, i.e., 45 mas. This assumption results in an inclination >81° and is much more constrained than the minimum inclination suggested by Liu & Leggett (2005) based on the size of the NICMOS PSF. Finally, since it is quite clear that Kelu-1B is still moving away from Kelu-1A, this minimum inclination estimate will only increase with time.

The period of the binary can be estimated using the 2005 July 31 separation (298 mas or 5.4 AU at the distance of Kelu-1) and the masses derived above. With the caveat that the most recent separation is not the maximum orbital separation, the calculated period is $\gtrsim$37 yr. This period is important for two reasons. First, it means that it is possible to obtain dynamical masses for the components in a reasonable time frame, something that has been done for only a few other binary brown dwarf systems (Brandner et al. 2004; Zapatero Osorio et al. 2004; Bouy et al. 2004). Second, this period means that the 1.8 hr period (or 3.6 hr if the variations are ellipsoidal in nature) reported by Clarke et al. (2002, 2003) is *not* due to this binary. Perhaps one of the components is itself a very close binary, or perhaps the shorter period is simply the rotation period for one of the components. In addition, the 60 km s^{-1} rotation velocity measured by Basri et al. (2000) on 1997 June 2 is from a composite spectrum. The maximum orbital velocity for Kelu-1AB is only ~3 km s^{-1}, which translates to a displacement of ± 0.09 and ± 0.08 Å for the Cs I and Rb I atomic lines used by Basri et al. This wavelength shift cannot account for the large equivalent widths of these lines (1.7 and 2.54 Å for Cs I and Rb I, respectively), so some other mechanism must be at work. In time it might be possible to separate the lines from each component using high-resolution spectroscopy and resolve some of these issues.

4. CONCLUSIONS

We have used the LGS AO system on the Keck II telescope to observe the binary brown dwarf Kelu-1AB. We have also reexamined the 1998 *HST* observations of Kelu-1 and show that the PSFs in those images are best fit by a binary object solution. Images from multiple epochs confirm the pair as having a common proper motion and demonstrate that Kelu-1B is still heading toward apoapsis. We constrain the inclination of a circular orbit to >81°. While this companion detection does rectify the overluminosity "problem," it cannot account for the 1.8 hr photometric period or the 60 km s^{-1} rotation velocity. Periodic monitoring of this system with high-resolution imaging and spectroscopy is needed to ensure that the maximum extent of the orbit is observed and measured, allowing for a more robust determination of the physical orbit.

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